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EDDY CURRENT HEATING IN THE METAL PISTON FOR THE FERMILAB 15 FOOT BUBBLE CHAMBER

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I. INTRODUCTION

Recent problems with the clamping of the fiberglass head to the truss work of the plastic piston used in Fermilab 15 foot Bubble Chamber have resulted in renewed interest in using the metal (stainless steel) piston. Since the only disadvantage of the metal piston is eddy current heating of the piston elements caused by its motion in the nonhomogeneous magnetic field, this note gives the calculation of that heating under various running requirements and attempts to define the operating limits of the chamber resulting from the use of the metal piston.

In Section II the equations for heating of conducting rings and disks moving in a magnetic field are derived (neglecting the effects of self inductance). Section III applies these equations to the various elements of the metal piston and then applies the correction for self and mutual inductance as derived in Appendix A. Also given are the expected piston heating for various running conditions and the distribution of the heat load among the chamber cooling loops. Section IV discusses the problems of removing the heat and the effect on picture quality. Section V summarizes the operating limits on the chamber using the metal piston.

In Appendix A more general equations for heating of conducting rings with self and mutual inductance are derived and approximately applied to the metal piston case in order to estimate the correction used in Section III. Finally, Appendix B gives the effect of the induced currents in the piston and Z section on the magnetic field.

II. HEATING EQUATIONS (neglecting mutual and self induction)[1]

In this section and in the remainder of this paper, the magnetic field, piston and Z section are all assumed to be cylindrically symmetric. This is almost exactly true for the 15 foot Bubble Chamber.

Consider a ring of radius r_1, (see Figure 1a) moving along the Z axis in a nonhomogeneous magnetic field. Then

$$\varepsilon = 10^{-8} \frac{d\phi}{dt} \qquad 1)$$

where ε is the induced EMF (volts) in the ring, ϕ is the flux (gauss cm^2) through the ring, and t is the time (seconds). Also

$$\phi = B_z A \qquad 2)$$

assuming that B_z (gauss), the magnetic field, in the Z direction, is not a function of r in the loop and where A (cm^2) is the area of the loop. Then

$$\frac{d\phi}{dt} = A \frac{dB}{dt} = \pi r_1^2 \frac{dBz}{dZ} \frac{dz}{dt} \qquad 3)$$

where Z (cm) is the position of the ring along the Z axis. The following (which is a good approximation to the actual case) is taken to be the position of the piston over one pulse

$$\begin{aligned} Z &= \frac{Z_o}{2} (1-\cos \omega t) \qquad 0 \le t \le T \\ Z &= 0 \qquad\qquad\qquad\quad 0 < t,\ t > T \end{aligned} \qquad 4)$$

where Z_o is the stroke (cm), T is the period (sec) and

$$\omega = \frac{2\pi}{T} \qquad 5)$$

From equation 4

$$\frac{dz}{dt} = \frac{\omega Z_o}{2} \sin \omega t \qquad 6)$$

so equation 3 becomes

$$\frac{d\phi}{dt} = \pi r_1^2 \frac{dB_z}{dZ} \frac{\omega Z_o}{2} \sin \omega t \qquad 7)$$

The EMF, ε will induce a current i (amp) in the ring.

$$i = \frac{\varepsilon}{R} \qquad 8)$$

where R is the resistance (ohms) of the ring and can be calculated from

$$R = \rho \frac{\ell}{th} \qquad 9)$$

where ρ is the resistivity of the ring material (ohm cm), $\ell = 2\pi r$ is its length, t is its thickness (cm), and h is its height. Putting equations 1, 7 and 8 together:

$$i = \frac{10^{-8} \; \pi r_1^2 \; \omega Z_o}{R2} (\frac{dB_z}{dZ}) \sin \omega t \qquad 10)$$

define

$$K = \frac{10^{-8} \pi^2 r_1^2}{T} (\frac{dB_z}{dZ}) \; Z_o \qquad 11)$$

then (using equation 5)

$$i = \frac{K}{R} \sin wt \qquad 12)$$

The heat W (joules) during one pulse is then

$$W = \int_0^T i^2 R dt \qquad 13)$$

or

$$W = \frac{K^2}{\omega R} \int_0^T \sin^2 \omega t \; d\omega t$$

finally

$$W = \frac{TK^2}{2R} \qquad 14)$$

which is the desired result for a simple ring. The current in the ring also produces a field which in turn affects the current (self inductance), but this has been neglected here.

Now consider a disk of radius r_1, (see Figure 1b) height h moving in the same way in the field. We consider a small element Δr at radius r which has a current Δi induced in it from equation 10

$$\Delta i = \frac{10^{-8} \pi \omega Z_o}{2 \Delta R} \left(\frac{dB_z}{dZ}\right) r^2 \sin \omega t \qquad 15)$$

where from equation 9

$$\Delta R = \rho \frac{2\pi r}{h \Delta r} \qquad 16)$$

The heat into the element Δr is

$$\Delta W = \int_0^T \Delta R \; \Delta i^2 \; dt$$

$$= \int_0^T \frac{1}{\omega} \left[\frac{10^{-8} \pi \omega Z_o}{2} \left(\frac{dB_z}{dZ}\right) r^2\right]^2 \frac{\Delta R}{\Delta R^2} \sin^2 \omega t \; d\omega t$$

$$\Delta W = \frac{1}{\omega}\left[\frac{10^{-8}\pi\omega Z_o}{2}\left(\frac{dB_z}{dZ}\right)\right]^2 \frac{h\pi}{2\pi\rho} r^3\Delta r \qquad 17)$$

The total heat to the disk is

$$W = \int_o^{r_1} \Delta W = \frac{1}{\omega}\left[\frac{10^{-8}\pi^2}{T} Zo \left(\frac{dB_z}{dz}\right)\right]^2 \frac{h}{2\rho}\int_o^{r_1} r^3 dr$$

$$W = \frac{K^2\ T\ h}{16\pi\rho} \qquad 18)$$

Again the effect of self inductance has been ignored.

If we define

$$R = \frac{8\pi\rho}{h} \qquad 19)$$

for the disk then equation 18 reduces to equation 14.

III. HEATING IN THE METAL PISTON

Figure 2 shows the simplified metal piston used for the calculations given in this Section. Table I gives the general parameters assumed and Table II the specific dimensions of each element. Also shown is the heat generated in each piece, W_N for one pulse assuming no inductance. By applying the correction for inductance obtained in Appendix A, i.e. that the heat generated in the moving parts of the piston is 85% of W_N and that 5% of the total no inductance heat will be put into the Z section ring, we obtain W_L for the general conditions given in Table I.

The heat generated by the motion of the metal piston must be removed by three of the bubble chamber cooling loops. The distribution of heat among these three cooling loops is expected to be as follows:

<u>The Main Heat Exchanger</u> (at the top of the chamber, which

cools chamber liquid) will take the heat from the top disk of the piston, the heat from the top 5¼" or 30% of the cylinder, the heat from the top 12" or 1/3 of the piston shaft, and 20% of the heat from the Z section ring.

The Pump Loop Heat Exchanger (which cools the piston ring area) will take the heat from the skirt hoop, the remaining 70% of the heat from the cylinder, and the remaining 80% of the heat from the Z section ring.

The Piston Plenum Heat Exchanger (which cools the gas and liquid under the piston) will take the heat from the bottom disk of the piston and the remaining 2/3 of the heat from the piston shaft.

Since the magnetic field in the 15' Bubble Chamber comes only from the current in the superconducting coils (no iron is used to return the magnetic flux), the field and the field gradients are directly proportional to the current in the coils. Using this fact and the equations in Section II, one can show that

$$W = W_L \left(\frac{Z_o}{4}\right)^2 \left(\frac{.07}{T}\right)\left(\frac{I}{5000}\right)^2 \qquad 20)$$

Where W is the heating at the running conditions of interest, W_L is given in Table II, Z_o is the piston stroke (inches), T is the expansion period (seconds), and I is the magnet current (amps). Using equation 20, the heat distribution as given above, and Table II we calculate the results given in Table III. The chamber conditions for H_2, light Ne-H_2 (21% atomic) and heavy Ne-H_2 (64% atomic) are based on actual running conditions; the conditions for D_2 are estimated. All results in this paper are based on full current, 5000 amps, in the magnet, but equation 20 can be used to easily get results for less than full current.

IV. REMOVING THE HEAT GENERATED BY THE METAL PISTON

Using the results given in Table III the average total heat load as a function of the average time between pulses is given in Figure 3 for the four chamber running conditions. The average heat load to be removed by the main, pump, and plenum cooling loops is given in Figures 4, 5 and 6. Table IV gives design capacities of the cooling loops of interest and the total refrigerator capacity for hydrogen running.[3] Also shown are the heat loads caused by the metal piston by one pulse per 10 seconds and one pulse per 5 seconds (i.e. double pulsing every 10 seconds) for H_2 running. For comparison, the ratio of the heat generated by the metal piston pulsed once per 5 seconds to the design capacity is shown in the table.

Table IV shows that the pump loop is most affected by using the metal piston. Consider the case of double pulsing in H_2 (average 1 pulse per 5 seconds). The actual load on this loop using the plastic piston is not well known, but if we estimate 0.5 kw is necessary for the other heat loads on the pump loop, we see that the pump loop is beginning to be overloaded and pulsing the chamber more often with the metal piston will not be possible. Other loads on the plenum loop are rather small so removing the heat generated by the metal piston with the plenum loop should not be a problem. The main loop should be able to remove the additional 0.468 kw without overloading, however, this removal of heat by the main loop would result in somewhat increased schlieren effects (local distortion of tracks and fiducials due to temperature gradients in the chamber liquid near the cameras). The cone loop, located in the chamber wall just above the piston, would be ideal to remove most of the heat without the schlieren effects. The design capacity of the cone loop is 0.45 kw. There have been considerable problems trying to use the cone loop in the past, mostly connected with the main heat exchanger and its interaction with the main loop. Now that the main heat exchanger problems have been solved and a clear need for the cone loop exists, I believe further attempts to use it are warrented. The total heat load from other sources on the hydrogen refrigerator is not well known, but for double pulse hydrogen running with the plastic piston, it was close to capacity. It is not clear that the refrigerator could take the additional 1.262 kw from the metal piston, but the addition of the hydrogen expansion engine (2.9 kw) should remove any problem with the total load on the refrigerator.

The above discussion assumes that only average heat loads are important. This is true of all cases but one, because large masses of metal and hydrogen and low heat transfer coefficients serve to average the pulsed heat input from the piston. The case of heat transfer from the top disk of the piston into the chamber liquid must be examined in more detail.

Starting with equation 17 the heat per unit area, q, generated in a disk is

$$q = \frac{\Delta W}{\Delta r 2\pi r} = \frac{1}{\omega}\left[\frac{10^{-8}\pi\omega Z_o}{2}\left(\frac{dB_z}{dz}\right)\right]^2 \frac{h}{4\pi\rho} r^2$$

$$q = \frac{TK^2 h}{8\pi^2 \rho r_1^2}\left(\frac{r}{r_1}\right)^2 \qquad 21)$$

$q = 125.56\ \frac{mj}{cm^2}$ at $r = r_1$ or allowing for inductance

$q = 106.73\ mj/cm^2$

This heat gives a temperature rise, ΔT, for one pulse:

$$\Delta T = \frac{q}{C_p\ m\ h} = 4.34^{\circ}K \qquad 22)$$

where[2] C_p = specific heat at $25^{\circ}K = 7.5\ \frac{mj}{gm^{\circ}K}$

m = density of iron = $7.87\ gm/cm^3$

The heat into piston top during the down stroke is 1/2 of equation 22 or

$$\Delta T = 2.17^{\circ}K \qquad 23)$$

Since this ΔT is sufficient to cause film boiling in liquid hydrogen, we must investigate the heat transfer from the piston top in more detail. The calculations will not be given here,[4] but it was assumed that all the temperature rise (equation 23) occurred at $t = 0$. The thermal conductivity of stainless steel used was $27\ mw/cm^{\circ}K$. Two cases were considered:

Case I: The piston top is covered by a 4 mil layer of scotchlite with thermal conductivity $1.28\ mw/cm^{\circ}K$.

Case II: No scotchlite on the piston and that the surface of the piston immediately assumes the liquid temperature.

The results for these two cases is given in Figure 7, and the results are quite different. In the first case, the initial heat transfer rate to the liquid is limited at 273 mw and about 3.6 mj are transferred to the liquid in 18 ms (T/4). (We assume that all the heat goes in at t = T/4 and the picture is taken at t = T/2). If we assume that all this heat is in a layer of liquid hydrogen 0.1 cm thick, then the temperature of the layer will be increased by 0.036°K, which should have no noticeable effect. In the second case, the initial heat transfer rate (for the model) is infinite and the heat transfer in the first 18 ms is about 14 mj. The high initial rate may cause film boiling to start, in which case the effect on the pictures would be very undesirable. Any areas on the top of the piston which are not covered by scotchlite should be covered by a thin (5 to 10 mil) layer of epoxy to limit the high initial rate of heat transfer to the liquid.

Figure 8 shows the heat transfer rates for longer times for the total heating per pulse with the result that most of the heat has been removed before the second pulse (.8 - .9 second) occurs. The conclusion is that the second pulse of a double pulse will start from essentially the same conditions as the first pulse.

V. CONCLUSIONS

1. The metal piston can be used for single pulsing (10 seconds between pulses) with almost no reservation for chamber running with D_2, H_2, light and heavy Ne-H_2. Multiple pulsing with heavy Neon should cause no problems because of the metal piston.

2. Double pulsing in hydrogen (2 pulses every 10 seconds)

is probably possible with moderate difficulties. Overloading of the pump loop and refrigerator may occur.

3. Pulsing more often than 2 pulses every 10 seconds in H_2, D_2 or light Ne-H_2 will not be possible with the metal piston.

4. Bare metal surfaces on the top of the metal piston should be covered with a thin (5 to 10 mil) layer of epoxy.

5. Attempts should be made to use the cone loop for H_2, D_2 or light Ne-H_2 running with the metal piston.

APPENDIX A

A more general case for heating of conducting rings moving in a magnetic field is shown in Figure 9. Applied to the 15' Bubble Chamber the moving ring 1 would be the piston and the fixed ring 2 would be the Z section flange (or cylinder) which closely surrounds the piston. Let

ϕ_o be the flux through the r_1 loop due to its motion in the magnetic field

ϕ_1 be the flux through the r_1 loop due to the current in loop 1

ϕ_2 be the flux through the r_1 loop due to the current in loop 2

ψ_1 be the flux through the r_2 loop due to the current in loop 1

ψ_2 be the flux through the r_2 loop due to the current in loop 2

then

$$i_1 = \frac{\varepsilon 1}{R_1} = \frac{10^{-8}}{R_1} \frac{d}{dt} (\phi_o + \phi_1 + \phi_2) \qquad \text{1a)}$$

$$i_2 = \frac{\varepsilon 2}{R_2} = \frac{10^{-8}}{R_2} \frac{d}{dt} (\psi_1 + \psi_2) \qquad \text{2a)}$$

which are generalized cases of equation 1. Using the cylindrical symmetry of the bubble chamber equation 2 generalizes to

$$\phi = 2\pi \int_o^r B_z \, rdr \qquad \text{3a)}$$

We now define

$$B_1 = -\ell_1 i_1, \quad B_2 = -\ell_2 i_2 \qquad 4a)$$

where the ℓ's are functions of r and give the field B_1 (B_2) at that radius due to a current in ring 1 (2). Then

$$\frac{d\phi_1}{dt} = \frac{-2\pi di_1}{dt}\int_o^{r_1} \ell_1 \, rdr \qquad 5a)$$

$$\frac{d\phi_2}{dt} = \frac{-2\pi di_2}{dt}\int_o^{r_1} \ell_2 \, rdr$$

$$\frac{d\psi_1}{dt} = \frac{-2\pi di_1}{dt}\int_o^{r_2} \ell_1 \, rdr$$

$$\frac{d\psi_2}{dt} = \frac{-2\pi di_2}{dt}\int_o^{r_2} \ell_2 \, rdr$$

From equations 5, 7 and 11

$$\frac{d\phi_o}{dt} = 10^8 \text{ K} \sin \omega t \qquad 6a)$$

We now define L_{ij} as constants relating the flux in loop i due to the current in loop j

$$L_{11} = 2\pi 10^{-8}\int_o^{r_1} \ell_1 \, rdr \qquad 7a)$$

$$L_{12} = 2\pi 10^{-8}\int_o^{r_1} \ell_2 \, rdr$$

$$L_{21} = 2\pi 10^{-8}\int_o^{r_2} \ell_1 \, rdr$$

$$L_{22} = 2\pi 10^{-8}\int_o^{r_2} \ell_2 \, rdr$$

Using equations 5a, 6a and 7a, equations 1a and 2a become

$$R_1\ i_1 = K \sin \omega t - L_{11}\frac{di_1}{dt} - L_{12}\frac{di_2}{dt} \qquad 8a)$$

$$R_2\ i_2 = - L_{21}\frac{di_1}{dt} - L_{22}\frac{di_2}{dt} \qquad 9a)$$

Using the requirement that at $t = 0$, $i_1 = i_2 = 0$ the solutions for these equations are

$$i_1 = a_1 \sin \omega t - c_1 \cos \omega t + c_1\ e^{-d\ \omega t} \qquad 10a)$$

$$i_2 = a_2 \sin \omega t - c_2 \cos \omega t + c_2\ e^{-d\ \omega t} \qquad 11a)$$

We now define

$$\beta_{11} = \frac{\omega L_{11}}{R_1}, \quad \beta_{12} = \frac{\omega L_{12}}{R_1}, \quad \beta_{21} = \frac{\omega L_{21}}{R_2}, \quad \beta_{22} = \frac{\omega L_{22}}{R_2} \qquad 12a)$$

Using the relations 12a, substitution of equations 10a and 11a in 8a and 9a gives the following conditions:

$$C_2 = \beta_{21}a_1 + \beta_{22}a_2 \qquad C_1 = \beta_{11}a_1 + \beta_{12}a_2 \qquad 13a)$$

$$a_2 = -\beta_{21}c_1 - \beta_{22}c_2 \qquad a_1 = \frac{K}{R_1} - \beta_{11}C_1 - \beta_{12}C_2$$

$$C_2 = \beta_{21}c_1 d + \beta_{22}C_2 d \qquad C_1 = \beta_{11}C_1 d + \beta_{12}C_2 d$$

To make the solution of equation 13a more workable we assume $r_1 = r_2$ which is approximately true for the 15' Bubble Chamber piston case. Then:

$$L_{11} = L_{21} = L_1 \qquad L_{12} = L_{22} = L_2 \qquad 14a)$$

defining $\delta = \frac{R_1}{R_2}$ equations 12a reduce to

$$\beta_1 = \beta_{11} = \frac{\omega L_1}{R_1}\ , \quad \beta_2 = \beta_{22} = \frac{\omega L_2}{R_2}\ , \quad \beta_{21} = \frac{\omega L_1}{R_2} = \beta_1 \delta$$

$$\beta_{12} = \frac{\omega L_2}{R_1} = \frac{\beta_2}{\delta} \qquad 15a)$$

and equations 13a become

$$C_2 = \beta_1 \delta a_1 + \beta_2 a_2 \qquad C_1 = \beta_1 a_1 + \frac{\beta_2}{\delta} a_2$$

$$a_2 = -\beta_1 \delta c_1 - \beta_2 C_2 \qquad a_1 = \frac{K}{R_1} - \beta_1 C_1 - \frac{\beta_2 C_2}{\delta} \qquad 16a)$$

$$C_2 = \beta_1 \delta a_1 + \beta_2 C_2 d \qquad C_1 = \beta_1 C_1 d + \frac{\beta_2 C_2 d}{\delta}$$

We define

$$\gamma = \beta_1 + \beta_2 \qquad 17a)$$

and the solutions to equations 16a are

$$d = \frac{1}{\gamma} \qquad a_1 = \frac{K\ (1 + \beta_2 \gamma)}{R_1\ (1 + \gamma^2)} \qquad 18a)$$

$$C = C_1 = \frac{\beta_1 K}{R_1\ (1 + \gamma^2)} \qquad a_2 = -\frac{K\ \delta \beta_1 \gamma}{R_1\ (1 + \gamma^2)}$$

$$C_2 = \frac{\delta \beta_1 K}{R_1\ (1 + \gamma^2)} = \delta c$$

Using equations 18a equations 10a and 11a become

$$i_1 = \frac{K}{R_1\ (1 + \gamma^2)} \left[(1 + \beta_2 \gamma) \sin \omega t - \beta_1 \cos \omega t + \beta_1 e^{-\frac{\omega t}{\gamma}} \right] \qquad 19a)$$

$$(0 \leq t \leq T)$$

$$i_2 = \frac{K\delta\beta_1}{R_1\ (1 + \gamma^2)} \left[- \gamma \sin \omega t - \cos \omega t - e^{-\frac{\omega t}{\gamma}} \right]$$

$$(0 \leq t \leq T)$$

After $t = T$, the piston stops moving and equations 8a and 9a become

$$R_1 i_1' = - L_1 \frac{di_1'}{dt} - L_2 \frac{di_2'}{dt} \qquad \text{20a)}$$

$$R_2 i_2' = - L_1 \frac{di_1'}{dt} - L_2 \frac{di_2'}{dt}$$

solving these equations and requiring that at $t = T$, $i_1 = i_1'$ and $i_2 = i_2'$ gives the results:

$$i_1' = \frac{-\beta_1 K \left(1 - e^{\frac{-2\pi}{\gamma}}\right)}{R_1\ (1 + \gamma^2)} e^{\frac{2\pi}{\gamma}} e^{\frac{-\omega t}{\gamma}} \quad (t \geq T) \qquad \text{21a)}$$

$$i_2' = - \frac{\beta_1 K\delta \left(1 - e^{\frac{-2\pi}{\gamma}}\right)}{R_1\ (1 + \gamma^2)} e^{\frac{2\pi}{\gamma}} e^{\frac{-\omega t}{\gamma}} \quad (t \geq T)$$

The heating in each loop over one pulse is then:

$$W_1 = \int_o^T R_1 i_1^2 dt + \int_T^\infty R_1 i_1'^2 dt \qquad \text{22a)}$$

$$W_2 = \int_o^T R_2 i_2^2 dt + \int_T^\infty R_2 i_2'^2 dt$$

substituting equations 19a and 21a in 22a gives the result:

$$W_1 = \frac{K^2 T}{2R_1} \left[\frac{1 + \beta_2{}^2}{1 + \gamma^2} + \frac{\gamma\ \beta_1\ (\gamma + \beta_2)\ \left(1 - e^{\frac{-2\pi}{\gamma}}\right)}{\pi\ (1 + \gamma^2)^2} \right] \qquad \text{23a)}$$

$$W_2 = \frac{K^2 T \delta \beta_1^2}{2R_1} \left[\frac{1}{1 + \gamma^2} - \frac{\gamma \left(1 - e^{\frac{-2\pi}{\gamma}}\right)}{\pi (1 + \gamma^2)^2} \right] \qquad 24a)$$

Comparing these equations with equation 14, we see that the effect of including inductances has been to multiply the heating W from equation 14 by a factor F_1 and to put some heat into the second loop equal to WF_2 where

$$F_1 = \frac{1 + \beta_2^2}{1 + \gamma^2} + \frac{\gamma \beta_1 (\gamma + \beta_2) \left(1 - e^{\frac{-2\pi}{\gamma}}\right)}{\pi (1 + \gamma^2)^2} \qquad 25a)$$

$$F_2 = \delta \beta_1^2 \left[\frac{1}{1 + \gamma^2} - \frac{\gamma \left(1 - e^{\frac{-2\pi}{\gamma}}\right)}{\pi (1 + \gamma^2)^2} \right] \qquad 26a)$$

An approximate solution to the first of equations 7a summed over all the pieces of the metal piston, gave $\beta_1 \cong 0.33$. The procedure used to make this approximation assumed that the effects of inductance did not change the distribution of currents in the metal piston, but only their overall magnitude. This assumption is approximately true for the metal piston geometry. The inductance of the fixed Z section ring was calculated from the formulas in reference 5 and results in $\beta_2 = 3.4$. To find δ to use in equation 26a, we find an effective resistance R_1 for the outer cylinder of the metal piston which would give the total heating of $W_N = 7.8481$ kj shown in Table 2.

R_1(effective) $= .633521 \times 10^{-3}$ ohm, $\delta = 7.3124$

Using equations 25a and 26a yields

$F_1 = .8524$, $F_2 = .0500$, $F_1 + F_2 = .9024$

Using equations 25a and 26a, Table V shows the variation of F_1, F_2, and $F_1 + F_2$ as a function of β_1 and β_2. The total, $F_1 + F_2$, is rather insensitive to β_1, or β_2, while there is somewhat more variation in the division of heat between the piston and the Z section ring. We will assume that the heating in the piston is 0.85 W_N and in the Z section is 0.05 W_N and conversatively estimate the error on the total heating to be ±5%.

APPENDIX B

Another possible problem in using the metal piston is the effect of the currents in the piston and Z section ring on the magnetic field of the chamber. This section shows that the effect is very small, less than 0.2% of the central magnetic field, and can be neglected.

The currents in the two rings are given by equations 19a. The time of interest is when the beam is injected into the chamber, which is a few milliseconds before the piston reaches its maximum stroke (T/2). The field at the center of a simple ring, due to a current in the ring, is

$$B = \frac{-2\pi i}{10r} \quad (\text{at } Z = 0) \qquad 1b)$$

or

$$B = \frac{-2\pi i r^2}{(r^2 + Z^2)^{3/2}} \qquad 2b)$$

We assume that ring #1 is the outer cylinder with resistance as given by equation 27a to lump all pieces of the metal piston into the outer cylinder. Other parameters are given in Tables I and II, and Appendix A. Using equations 19a and 1b we calculate the fields shown in figure 10. The sum of the fields from rings #1 and #2 is always less than 42.5 Gauss to be compared with the central chamber field of 29,500 Gauss or 20,800 Gauss at the piston.

The negative value for the sum in figure 10 means that this field tends to oppose the change in flux through the piston. For the 15' Bubble Chamber geometry, this means that field near the piston will be slightly higher because of the induced currents.

Equation 2b gives the falloff of this small additional field as you go away from the piston.

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TABLE I

GENERAL PARAMETERS FOR THE 15' BUBBLE CHAMBER PISTON

Resistivity of 304 Stainless Steel[2]	ρ = 5.53 x 10^{-5} ohm cm (at 25°K)
Chamber Period	T = 0.07 sec.
Piston Stroke	Z_o = 4.0 inch

TABLE II

SPECIFIC DIMENSIONS AND HEATING IN THE METAL PISTON ELEMENTS

	Element	Shape	r_1 cm	t cm	h cm	$\langle \frac{dB_z Z_o}{dZ} \rangle$ gauss	K	R ohm	W_N KJ	W_L KJ
1.	Outer Cylinder	ring	89.726	0.635	44.45	1050	11.9187	$1.10453\text{x}10^{-3}$	4.5014	3.8262
2.	Top	disk	90.043	-	.4166	1080	12.3460	$3.33615\text{x}10^{-3}$	1.5991	1.3592
3.	Bottom	disk	90.043	-	.4166	990	11.3171	$3.33615\text{x}10^{-3}$	1.3437	1.1421
4.	Skirt Hoop	ring	89.726	0.1499	12.7	990	11.3171	$1.63764\text{x}10^{-2}$	0.2737	0.2326
5.	Shaft	ring	13.731	2.54	91.44	1040	0.276465	$2.05417\text{x}10^{-5}$	0.1302	0.1107
6.	Z Section	ring	96.52	12.7	30.48	-	-	$8.66370\text{x}10^{-5}$	-	.3924
	TOTAL								7.8481	7.0632

TABLE III

CHAMBER COOLING LOOP LOADS FOR SEVERAL RUNNING CONDITIONS

Chamber Fill	D_2	H_2	Light Ne-H_2	Heavy Ne-H_2
Stroke Z_o (inch)	4.0	3.5	3.75	2.0
Period T (sec.)	0.07	0.06	0.09	0.10
Ratio W/W_L	1.000	0.8932	0.6836	0.175
Main Loop (KJ/pulse)	2.6224	2.3423	1.7927	0.4589
Pump Loop (KJ/pulse)	3.2249	2.8805	2.2045	0.5644
Plenum Loop (KJ/pulse)	1.2159	1.0861	0.8312	0.2128
Total (KJ/pulse)	7.0632	6.3089	4.8284	1.2361

TABLE IV

COOLING CAPACITIES AND HEAT LOADS DUE TO THE METAL PISTON DURING H_2 RUNNING

LOOP	DESIGN CAPACITY KW	HEAT GENERATED BY METAL PISTON: 1 PULSE PER 10 SEC KW	HEAT GENERATED BY METAL PISTON: 1 PULSE PER 5 SEC KW	HEAT (1/5 SEC.) / DESIGN CAPACITY %
Main	4.0	.234	.468	12%
Pump	1.0	.288	.576	58%
Plenum	0.6	.109	.218	36%
Refrigerator (TOTAL)	6.7	.631	1.262	19%

TABLE V

VARIATION OF THE F_1 AND F_2 PARAMETERS WITH β_1 AND β_2

F_1

$\beta_2 \backslash \beta_1$	.28	.33	.38
2.9	.8588	.8367	.8154
3.4	.8727	.8524	.8329
3.9	.8844	.8658	.8478

F_2

$\beta_2 \backslash \beta_1$	.28	.33	.38
2.9	.0475	.0643	.0830
3.4	.0369	.0500	.0646
3.9	.0293	.0399	.0517

$F_1 + F_2$

$\beta_2 \backslash \beta_1$	.28	.33	.38
2.9	.9063	.9010	.8984
3.4	.9096	.9024	.8975
3.9	.9137	.9056	.8996

FIGURE CAPTIONS

1. Geometry of a ring (a) and a disk (b) used for the heating calculations in Section II.
2. Geometry of the metal piston used for the heating calculations in Section III. Element numbers refer to Table II.
3. Total heating due to the metal piston for the four chamber running conditions given in Table III.
4. Heat which must be removed by the main cooling loop.
5. Heat which must be removed by the pump cooling loop.
6. Heat which must be removed by the piston plenum cooling loop.
7. Heat transfer rate from the outer edge of the top disk of the piston to the chamber liquid during the first part of the pulse. One half of the total heat is assumed to go into the top disk at t = 0. Case I assumes that the piston top is covered by scotchlite, while Case II is for bare metal.
8. Heat transfer rate from the outer edge of the top disk of the piston to the chamber liquid after the pulse. All the heat for the pulse is assumed to go into the top disk at t = 0. Case I and II are the same as for Figure 7.
9. Geometry of the fixed and moving rings used in Appendix A to calculate the heating including the effects of mutual and self inductance.
10. Magnetic fields due to the currents in loops #1 and #2 and their sum during the time which beam is expected to be injected into the chamber.

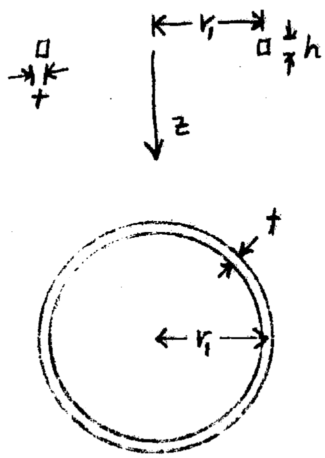


Figure 1a

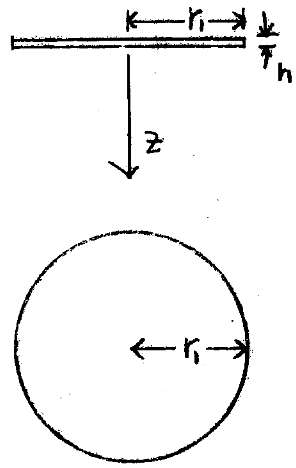


Figure 1b

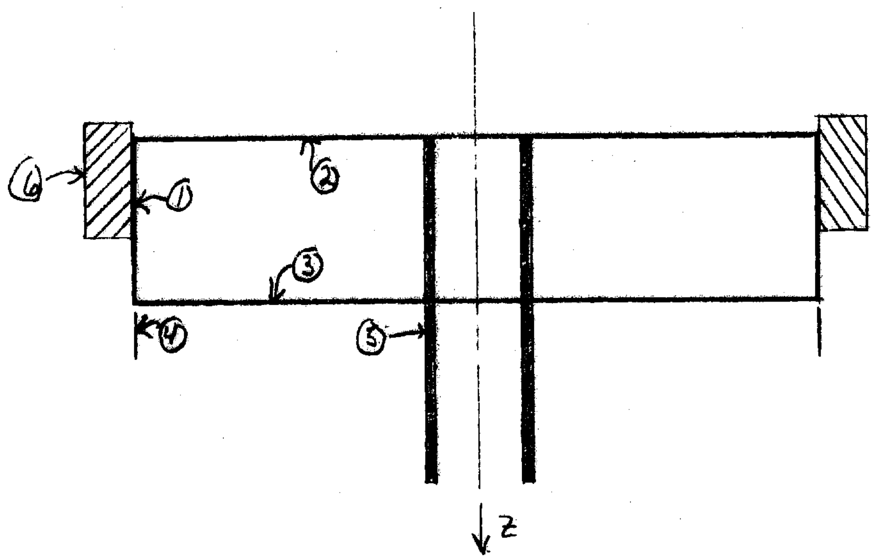


Figure 2

Total Heating due to Metal Piston

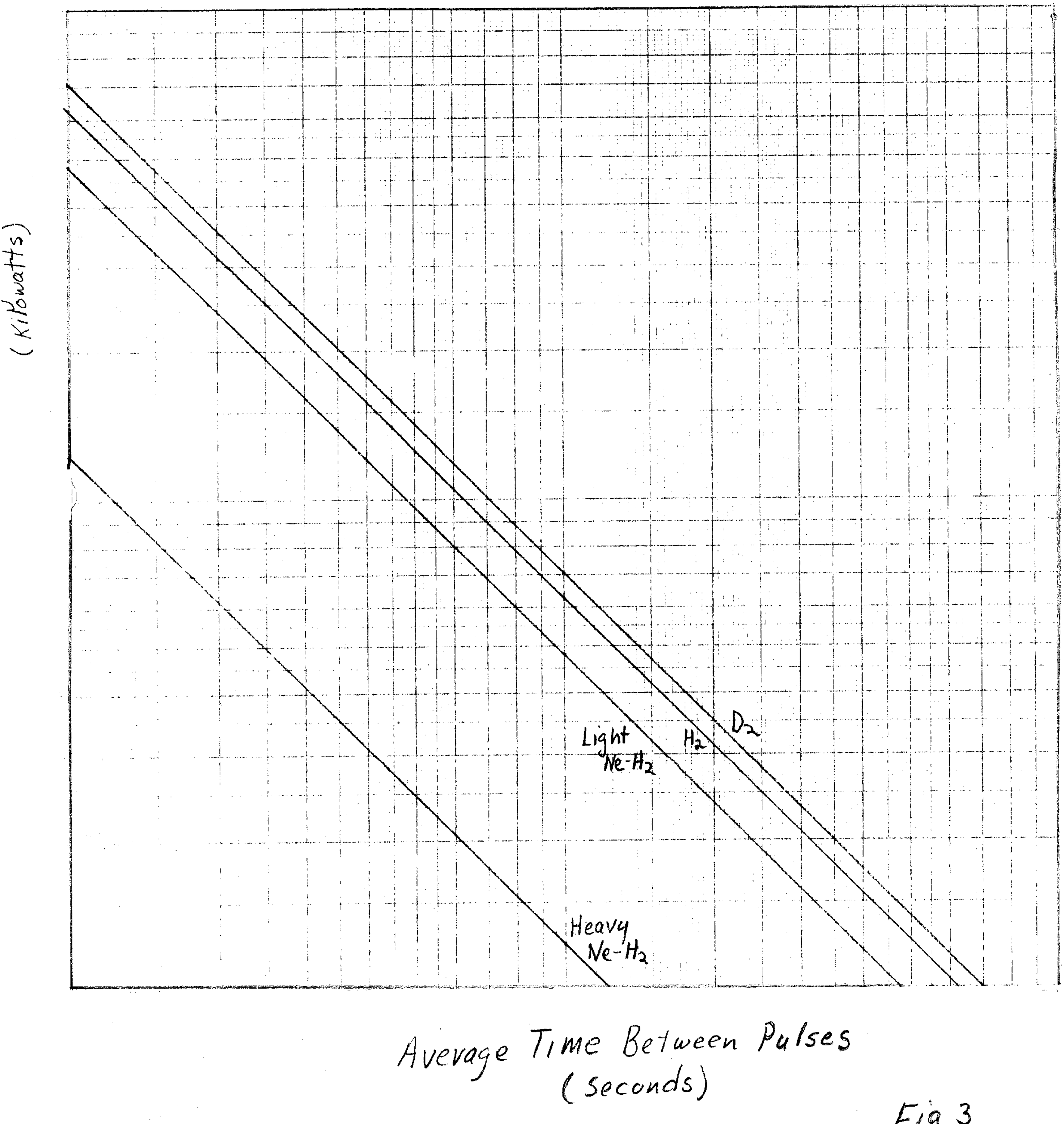


Fig 3

Heat to Main Cooling Loop

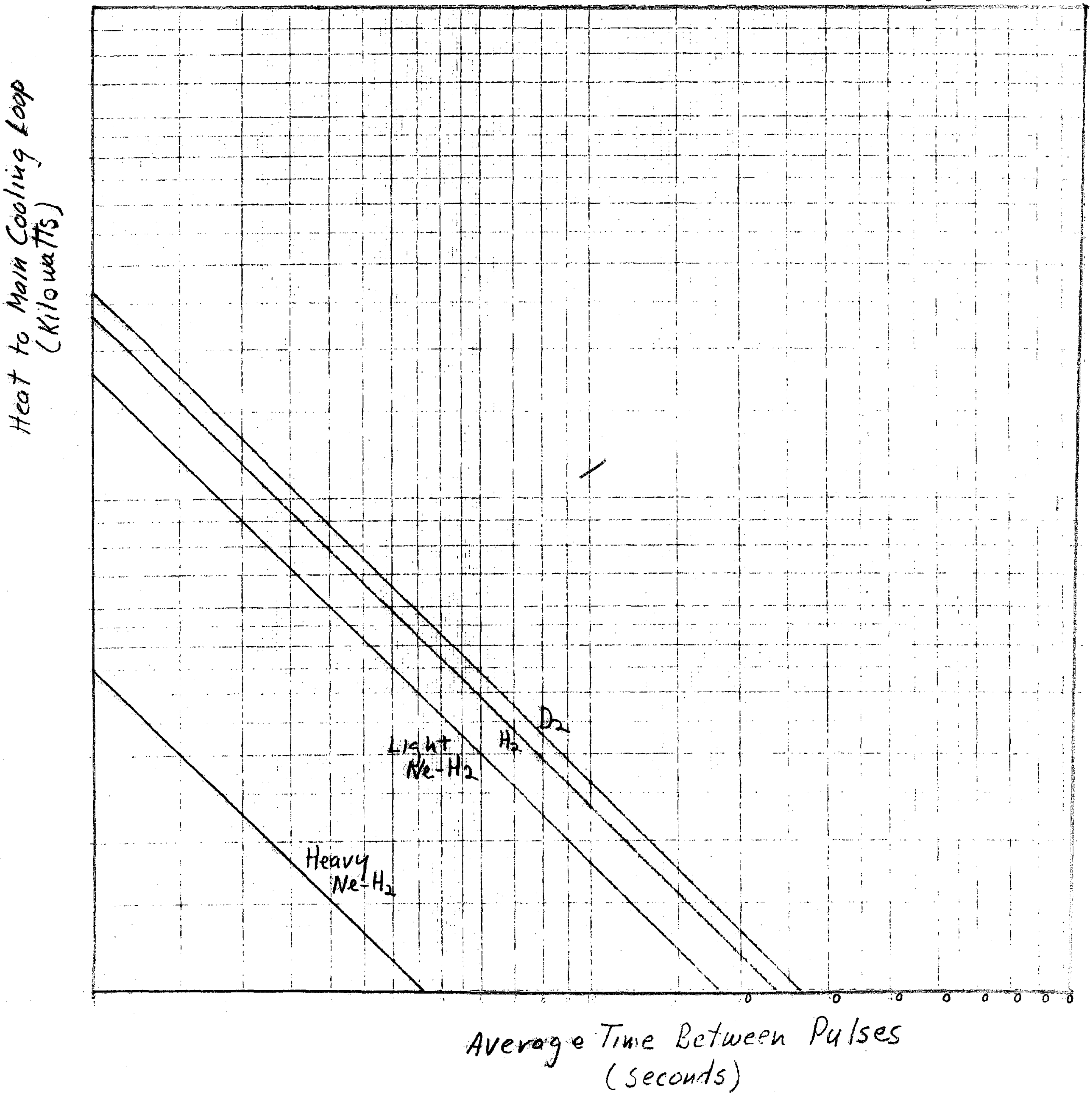
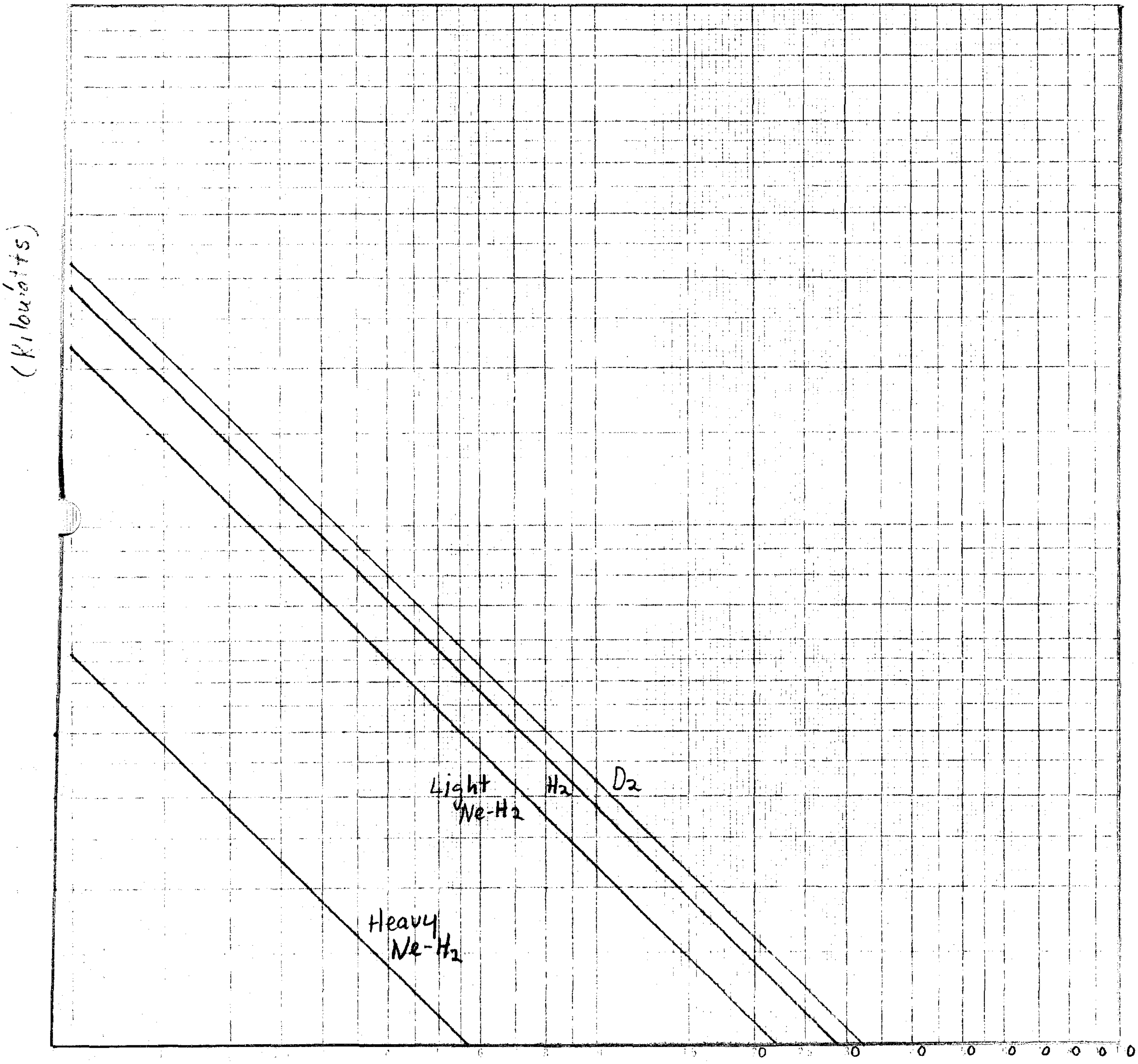


Figure 4

Heat to Pump Loop



Average Time Between Pulses
(Seconds)

figure 5

Heat to Plenum Loop

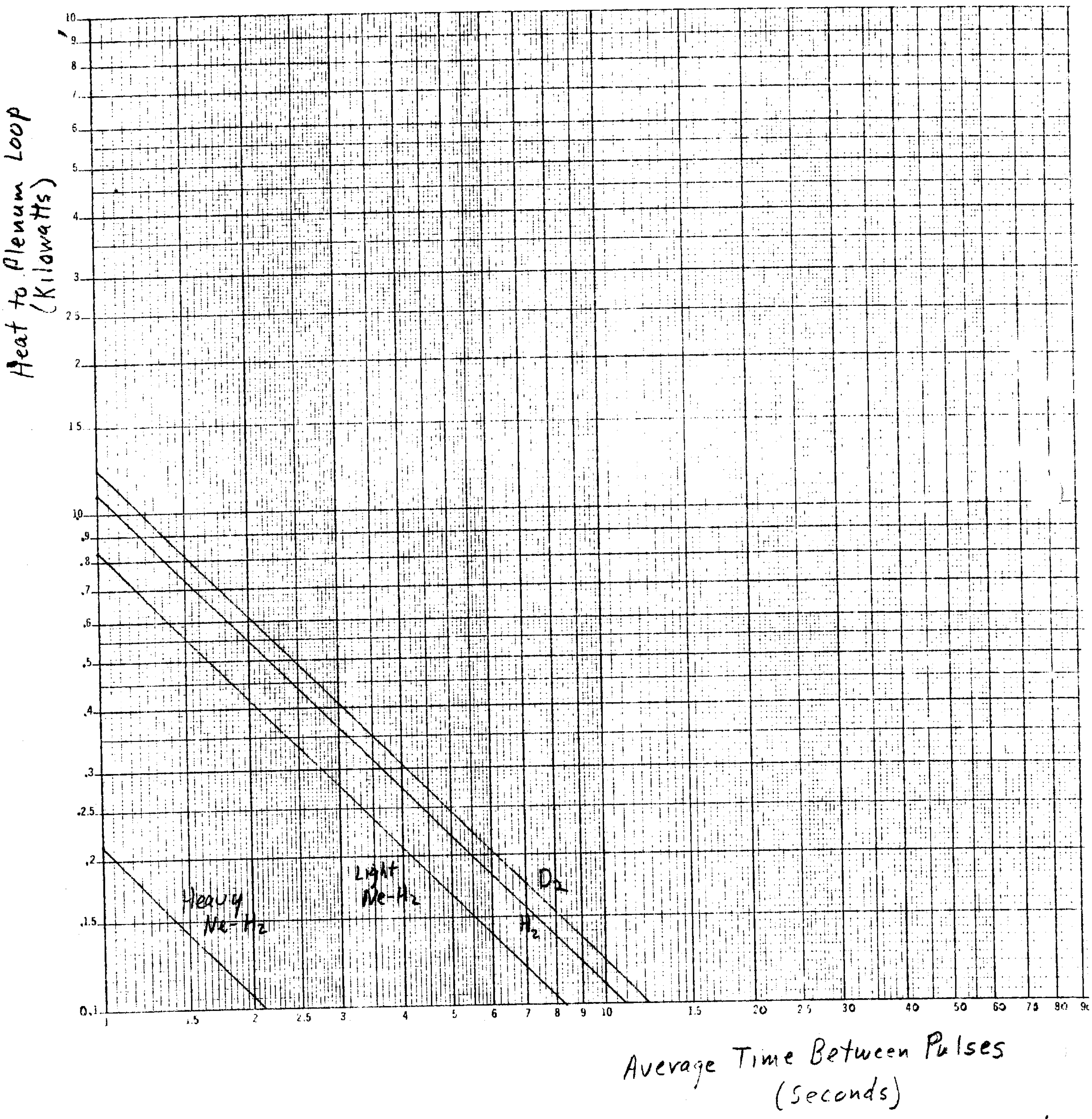


Fig 6

Figure 7

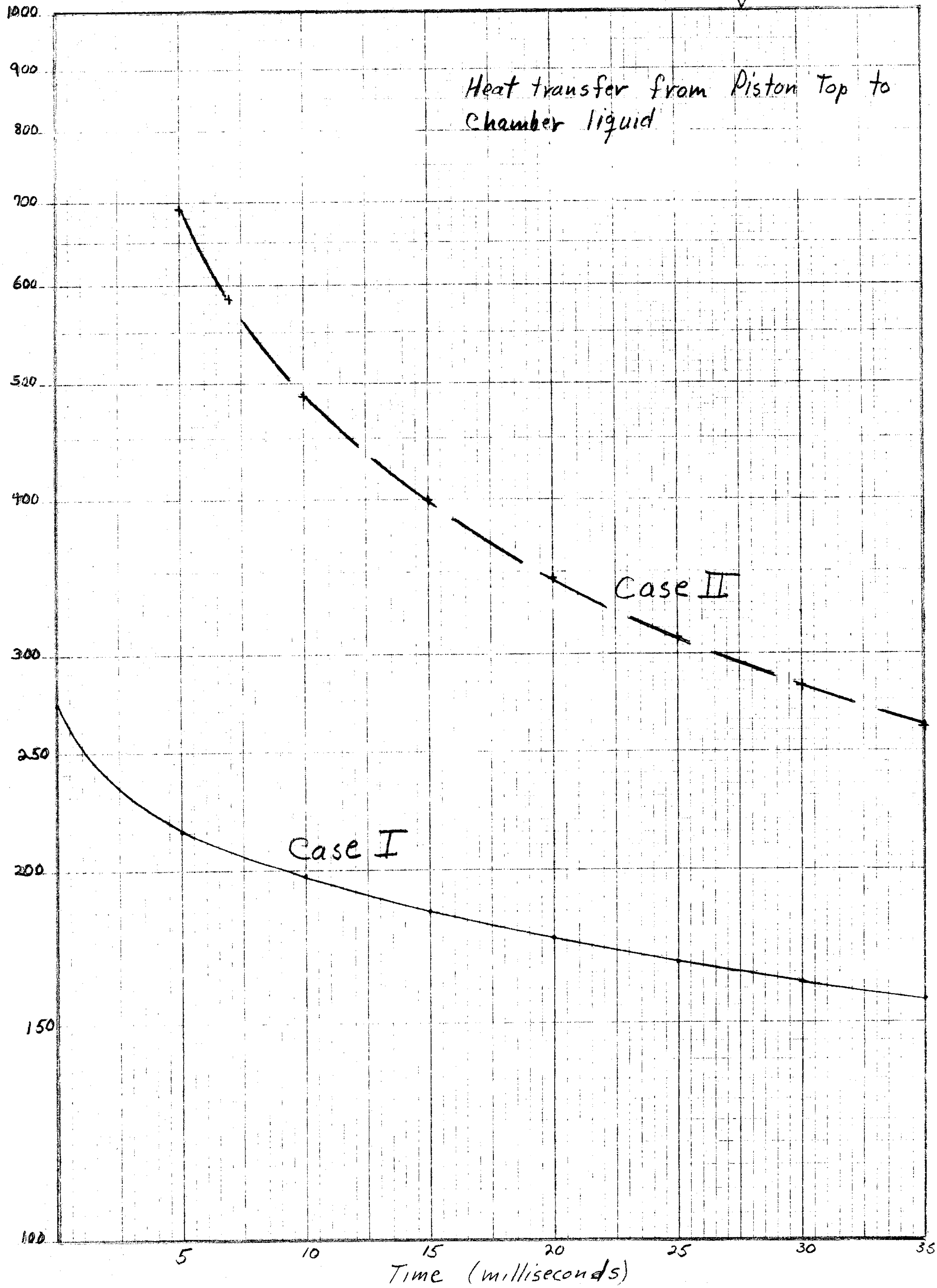
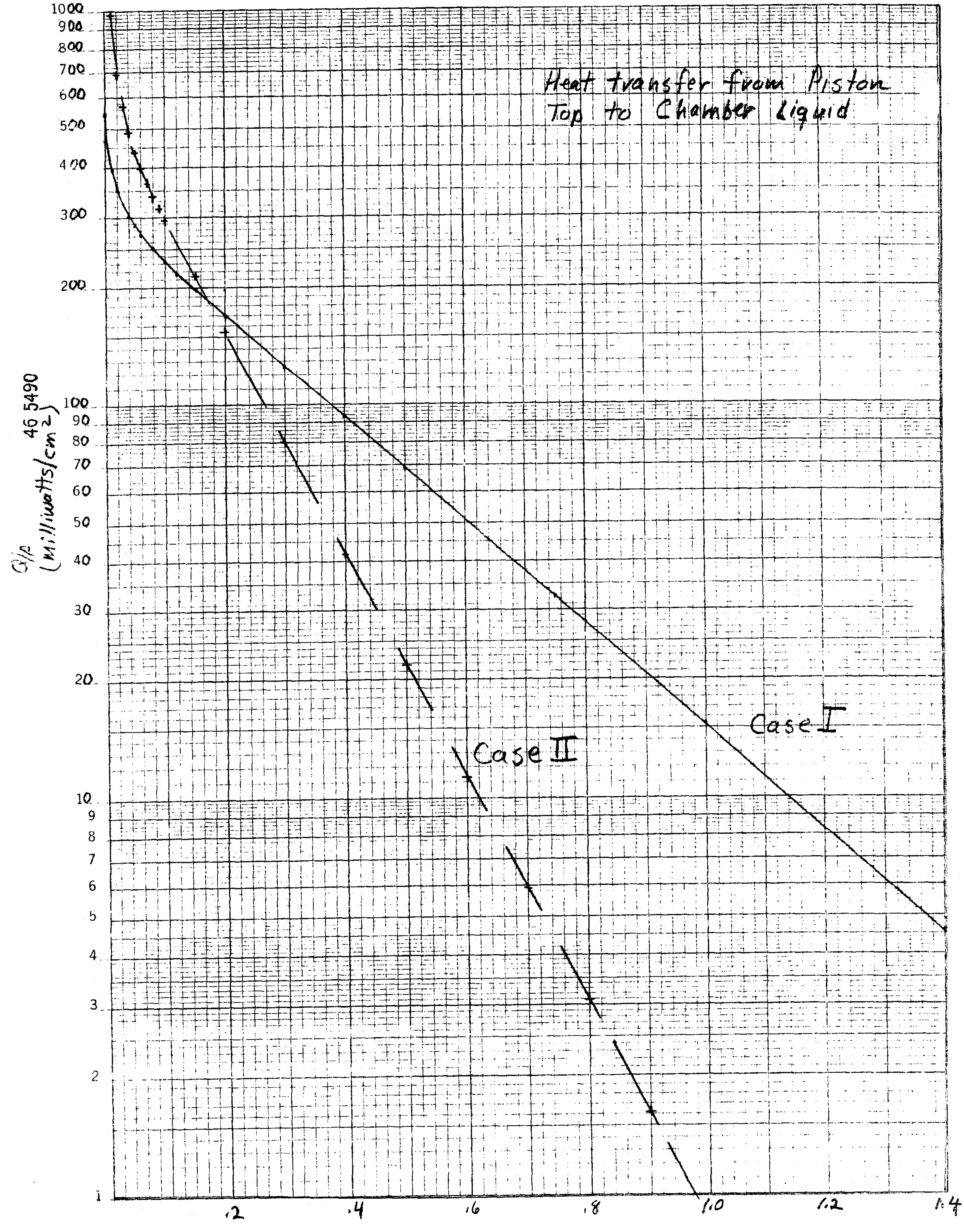

Heat transfer from Piston Top to Chamber liquid
Case I
Case II
1000
900
800
700
600
500
400
300
250
200
150
100
5
10
15
20
25
30
35
Time (milliseconds)

 Figure 8


Heat transfer from Piston Top to Chamber Liquid
Q/A (milliwatts/cm²)
46 5490
1000
900
800
700
600
500
400
300
200
100
90
80
70
60
50
40
30
20
10
9
8
7
6
5
4
3
2
1
.2
.4
.6
.8
1.0
1.2
1.4
Case I
Case II

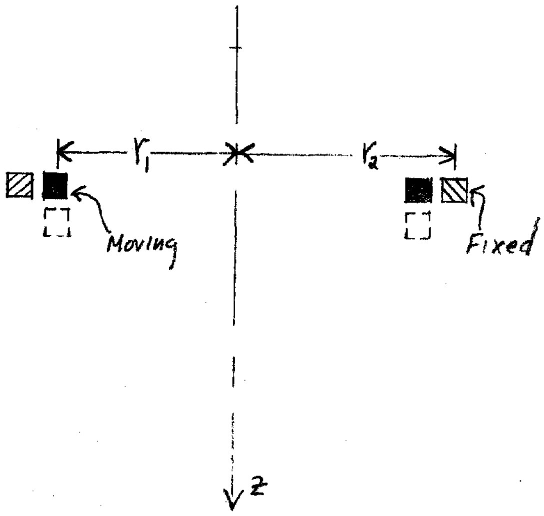
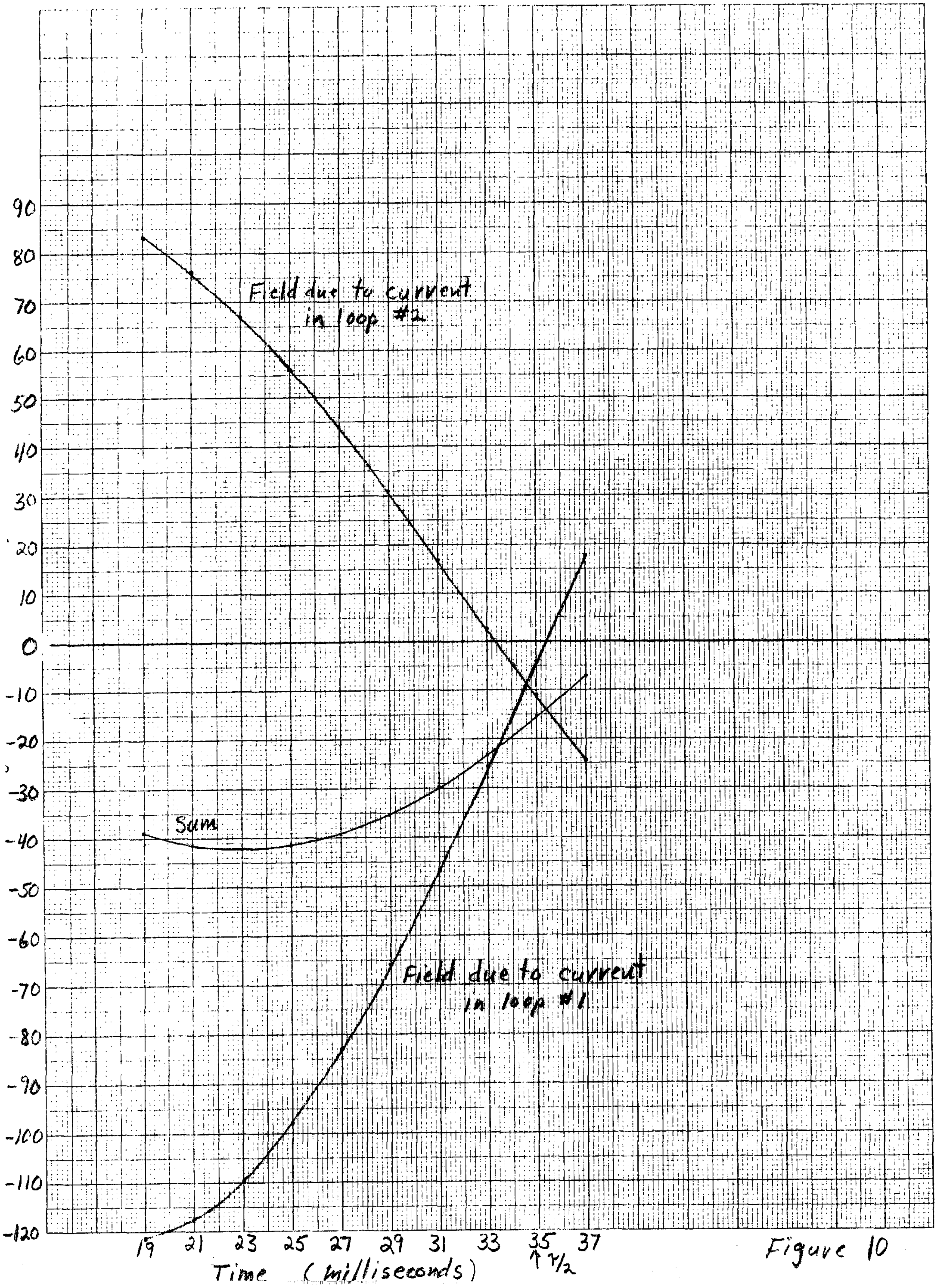


Figure 9



90
80
70
60
50
40
30
20
10
0
-10
-20
-30
-40
-50
-60
-70
-80
-90
-100
-110
-120
Field due to current in loop #2
Sum
Field due to current in loop #1
19 21 23 25 27 29 31 33 35 37
↑ T/2
Time (milliseconds)

Figure 10